

Energy-environmental-economic assessment of green retrofit policy to achieve 2050 carbon-neutrality in South Korea: Focused on residential buildings



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ABSTRACT

To achieve carbon emission reduction target (CERT) by 2030 and carbon-neutrality in 2050, it is important to actively reduce the emission gap in the private building sector. However, the ongoing COVID-19 pandemic and the Russian-Ukraine war are threatening the green remodeling policy (GRP) worldwide. Therefore, this study analyzed energy consumption savings, GHG emission reduction, and net present value when applying green remodeling to a private building to predict whether or not the current GRP could achieve 2030 CERT and 2050 carbon-neutrality. The main findings are as follows. First, yearly electricity and gas consumption of 84.97 m² type households can be reduced by 6.19% and 15.58% through green remodeling. Second, based on the energy saving, yearly GHG emission can be reduced about 0.34tCO_{2eq}. Third, the economic feasibility of green remodeling cannot be achieved via the current policy, and NPV₁₇ decreases up to USD-51,485 depending on the credit loan interest rate and the green remodeling interest subsidy program. In other words, it is difficult to reach 2030 CERT and 2050 carbon-neutrality via the current policy. Therefore, the South Korean government is required to reorganize financial policies, establish active systems, increase public awareness of the policy, and improve energy efficiency technology.

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1. Introduction

Emissions from fossil fuels rebounded by 4.8% after a 5.4% drop in 2020 due to restrictions that COVID-19 pandemic brought [1]. Lifting of the pandemic lockdown is facilitating the recovery of economic losses, but it is resulting in higher CO₂ emissions compared to the pre-pandemic level [2]. The United Nations Environment Program reported that the new pledges for 2030 would reduce CO₂ emissions by only 7.5% while 30% is required for managing the global average temperature rise below 2°C compared to pre-industrialization period, keeping the emissions gap large [3]. Among Group of 20 members, South Korea, along with Australia, Brazil, Canada, Mexico and the United States of America, suggested to enhance policies to achieve the prior nationally determined con-

tributions (NDC). In a related move, the South Korean government announced a plan to promote Green New Deal (GND), while declaring its updated NDC in 2021. According to the GND 2021 promotion plan announced by the Ministry of Environment, a budget of about USD 50 million was to be invested in the GRP, which is one of the 10 major tasks of South Korea's GND [4]. The green remodeling is also known as green retrofit, involving thermal retrofitting of aging buildings, replacement of windows and insulation in aging buildings, and improving the performance of heating and cooling system to reduce CO₂ emissions [5]. According to the International Energy Agency, the global share of the building sector in the final energy consumption is about 30%, and existing buildings will account for about two third of the building stock by 2040 [6]. It indicates that while it is important to construct new passive houses and zero-energy buildings, it is also critical to improve the energy efficiency of the existing buildings.

The GRP is conducted globally in various forms to reduce CO₂ emissions. The United Kingdom is implementing the Green Deal

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Nomenclature

CAGR	compound annual growth rate	KCGA	Korea City Gas Association
CERT	carbon emission reduction target	KEPCO	Korea Electric Power Corporation
CV(RMSE)	coefficient of variation of the root mean square error	LCC	life cycle cost
DOE	Department of Energy	LH	Korea Land and Housing Corporation
Eco-PTZ	Éco-prêt à taux zero	MBE	mean bias error
ECOS	Bank of Korea Economic Statistics System	MOLIT	Ministry of Land, Infrastructure and Transport
EPC	Energy Performance Certification	NDC	national determined contributions
GHG	greenhouse gas	NPV	net present value
GND	Green New Deal	REB	Korea Real Estate Boarding
GRCC	Green Remodeling Creation Center	vCAGR	variant compound annual growth rate
GRISB	Green Remodeling Interest Subsidy Business		
GRP	green remodeling policy		
IQR	interquartile range		

project to encourage thermal retrofitting of existing buildings [7]. In Germany, 2% of existing buildings are targeted to be retrofitted annually, and the Germany Federal Development Bank suggests energy performance standards for existing buildings that are essential for financial support of green remodeling [8,9]. According to the Ministry of Land, Infrastructure and Transport (MOLIT), 75% of buildings in South Korea are aging buildings aged 15 or above and are subject to GRP as of 2020 [10]. As part of South Korea's GND promoted from 2020, green remodeling were conducted on public buildings such as national daycare centers and public health centers, and about 800 cases were carried out by 2020 [4]. However, the proportion of public buildings in South Korea was only 2.86% as of 2016, and it was essential to extend the scope of the GRP to include private buildings in order to achieve enhanced NDC [11]. Consequently, a project to partially subsidize loan interest rates for construction costs was promoted to revitalize the private green remodeling, and a budget of about USD 7 million was executed in 2022 [12].

To revitalize the green remodeling, each country has implemented various support policies and projects, such as providing subsidies and tax benefits [13–16]. Among them, the most common method is to support the loan interest for construction costs. The government of France has been making the green remodeling mandatory with the standard for thermal retrofitting being the Energy Performance Certification (EPC) [17]. EPC experts evaluate the energy performance of buildings and give ratings that are required to be shared for building rentals or sales. Since 2005, the government of France has implemented the Éco-prêt à taux zero (Eco-PTZ), which is the zero interest rate loans for the green remodeling [15]. Germany also uses EPC evaluations while the Federal Development Bank provides another standard called KfW Efficiency House that is reflected when providing subsidies or low-interest loans [13,18]. The United States does not implement a national GRP, but there are various kinds of GRP that are at state or city-level. For example, in Alabama, the AlabamaSAVES program is provided and the loan interest rate it proposed is fixed at 2%. The South Korean government supports up to 3% interest according to the support standards for the energy improvement cost of existing buildings in order to revitalize private green remodeling [5].

In 2022, the outbreak of the war in Ukraine caused uncertainties about the global economy due to disruptions in the supply of energy and grains as well as the increase in price volatility. The International Monetary Fund has noted that the war in Ukraine has led to a sharp rise of interest rates, while the Federal Reserve System has approved to raise interest rate to 3.25% in September 2022, which is 0.75 point higher than the previous rate [19,20]. The Federal Reserve System has issued another 0.75 point hike, prompting the rates to post a record high since 2008 [21]. These

hikes are leading to the rise in benchmark interest rates proposed by central banks around the world, including South Korea [22]. Because the benchmark interest rate announced by the Federal Reserve System affects the overall national economy, including foreign investment funds, exchange rates and prices, the benchmark interest rate of each country varies depending on the trend of changes in the interest rate of the USA. Bank of Korea issued to raise its interest rate to 3.0% in October 2022, after the 0.75 point increase in the USA. This 'big step' rate hike affects the interest rate of the overall market. For example, South Korea's national housing bond interest rate increased from 2.256% in October 2021 to 4.522% in October 2022 [23]. The interest rate hike resulting from unstable international economic situation is expected to serve as a critical risk factor to the green remodeling activation policy implemented in each country, including South Korea.

Aside from this critical risk due to hikes in interest rates worldwide, the green remodeling activation policy fails due to a lack of economic feasibility of the project itself. A typical example is the Green Deal in the UK. The analysis found that the Green Deal policy did not increase the participation rate of householders and failed to achieve value for money [24]. In reality, the interest rate on household loans was too high, and CO₂ emission reduction through the policy was only 0.3 MtCO₂/year [25]. Even for the GRP in Germany, which is relatively successful, the degree of thermal retrofit implementation was 0.8%, compared to the government's annual target of 2% [26]. In addition to the interest rate hikes, there is a risk that GRP is scaled down due to problems in terms of economic feasibility of the existing GRP carried out in each country. However, since reducing the CO₂ emissions gap is also an urgent international concern, active countermeasures need to be taken to prevent the reduction of GRP due to interest rate hikes. It is highly necessary to analyze the effectiveness of the GRP. However, although previous studies were carried out to derive measures to revitalize green remodeling in each country, including South Korea, and to analyze the existing measures, there is a lack of research to analyze the current GRP in consideration of the recent interest rate hikes. Kim et al. conducted a survey to investigate the major drivers and barriers of green remodeling in South Korea [27]. The authors provided findings that can be helpful for green remodeling operators to activate green remodeling further, but they did not propose specific measures or problems with the existing interest support programs.

Therefore, this study aims to analyze the feasibility of the current GRP considering the recent interest rate hikes and the interest support rate of the green remodeling subsidy projects in South Korea. Based on the results of the analysis, policy directions will be proposed. To achieve this, the following methodologies are proposed along with case studies. First, a database of green remodel-

ing interest support business was established and energy performance simulation was carried out using *EnergyPlus* and *Design-Builder* software. Then, economic assessment of green remodeling was conducted using the life cycle cost (LCC) analysis approach. Based on the previous analysis results, South Korea's GRP was proposed by comparing the national carbon emission reduction target (CERT) with the energy consumption savings through green remodeling.

2. Material and methods

2.1. Step 1: Selection of target building

In this study, three standards were applied to select the target building.

First, the green remodeling creation center (GRCC) under the control of MOLIT in South Korea defines buildings aged 15 years or more as aging buildings [28]. Therefore, as of 2022, a building constructed before 2008 was selected as the target building. Second, the Korea Real Estate Board (REB) classifies households in apartment complexes into six types according to the floor area: (i) 40 m² or less; (ii) more than 40 m² and less than 60 m²; (iii) more than 60 m² and less than 85 m²; (iv) more than 85 m² and less than 102 m²; (v) more than 102 m² and less than 135 m²; (vi) 135 m² or more [29]. As of 2021, a total of 11,948,544 EA fall under the category of residential type classified as an apartment complex in South Korea. Among them, the number of households with floor areas that are greater than 60 m² and less than 85 m² is 5,382,655 EA, accounting for about 45% [29]. Therefore, in this study, households with a floor area greater than 60 m² and less than 85 m² were selected as subjects. Third, building information (i.e., regional data, building type, construction completion years, and physical data) is needed to calculate costs (i.e., initial investment cost, repair cost) and benefits (i.e., energy consumption saving, carbon credit (i.e., Korea certified emission reductions (KCEs)) attributable to the application of green remodeling. REB collects various data for apartment complexes with households of 300 EA or more and discloses them to the apartment housing management information system [30]. Therefore, this study attempted to select an apartment complex with households of 300 EA or more and whose data are continuously updated in the system. Consequently, in this study, 'D' apartment complex located in Pohang, South Korea was selected as the target building. In reality, green remodeling was applied to 'D' apartment complex as one of the GRCC project cases in 2016.

2.2. Step 2: Database establishment

The database used in this study consists of three types: (i) loan programs for construction cost; (ii) building information; and (iii) information for economic assessment.

2.2.1. Loan programs for construction cost

Loans for construction cost are required when conducting green remodeling. There are mainly three options for people who need construction cost loans for green remodeling: (i) green remodeling interest subsidy program; (ii) mortgage loan program; and (iii) credit loan program.

- **Green remodeling interest subsidy program:** Korea Land and Housing Corporation (LH) under MOLIT is mainly supervising policies to activate green remodeling in South Korea. The major interest subsidy program for all regions in Korea is called Green Remodeling Interest Subsidy Business (GRISB). The main purpose of the program is to improve the energy performance of

private buildings by supporting the interest rate of construction cost loans. The program is intended for all types of private buildings applied with one or more construction works to improve building energy performance, such as insulation, airtightness and window performance improvements. If the energy performance improvement ratio is more than 20% after green remodeling is applied, or if the energy efficiency rating for windows is 3 or higher, support for up to 3% interest is provided within the limit of USD14,015.42. The loan can be repaid in regular installments for a total of 60 months [5].

- **Mortgage loan program:** The mortgage loan program is used to finance relatively large expenses such as building remodeling costs. It is a residential mortgage loan program where a loan is provided from a financial institution with the house as the collateral for the mortgage. The mortgage loan program demands collateral to secure the loan and requires a good credit record, but interest rates are generally lower than credit loans. It should be noted that loan interest rates and repayment periods vary depending on the financial institution. Therefore, the data from the Bank of Korea Economic Statistics System (ECOS), which collects and analyzes the data of the 1st financial bank, were considered reliable and were used in this study. As of September 2021, the interest rate on a loan from the mortgage loan program is 4.43%, and the repayment period is 35 years [23].
- **Credit loan program:** The credit loan program provides a loan from a financial institution based on the credit of an individual or a company without requiring collateral such as real estate. According to the ECOS data, the loan interest rate of the credit loan program was 6.62%, and the repayment period was 10 years in September 2021 [23].

2.2.2. Building information

In this study, the following building information was collected for energy performance assessment and economic assessment: (i) regional data; (ii) building type and construction completion year; and (iii) physical data.

- **Regional data:** The regional data of the target building is required for energy simulation and economic assessment. First, for energy simulation, latitude, longitude and elevations are needed along with the corresponding climate information [31]. The surrounding environment, e.g., monthly outdoor air temperature, varies depending on the building location and this consequently affects energy consumption. Regional data is also needed for economic assessment for the same reason. The green remodeling analysis system developed to support green remodeling decision-making based on the analysis of green remodeling effects and provision of technical information provides green remodeling construction costs and performance databases for each verified scenario [32]. MOLIT presents and applies energy-saving design standards for buildings to the following regions in South Korea: (i) Central 1, (ii) Central 2, (iii) Southern and (iv) Jeju [33]. Because the thermal transmittance standards vary among regions, the construction costs were also set differently for each region.
- **Building type and construction completion year:** The green remodeling construction cost database for each scenario provided by the green remodeling analysis system provides construction cost database according to the building type [32]. In addition, information on the construction completion year is needed because the legally determined thermal transmittance standards differ according to the year. The construction completion year is also required to analyze the LCC for economic assessment.

- **Physical data:** Physical data such as floor area, building envelope insulation and lighting performance are required to perform energy simulation [34,35]. As described in Section 2.1, households with a floor area of more than 60 m² and less than 85 m² were selected in this study. For the insulation material, the legal standard for thermal transmittance of the construction completion year was complied with [33], and lighting performance information data were collected from the ASHRAE standard [36].

2.2.3. Data for economic assessment

LCC analysis was conducted for economic assessment in this study and the data required for the assessment are as follows: (i) real discount rate, (ii) construction and repair cost, (iii) benefit.

- **Real discount rate:** Future costs are converted into present values in the LCC analysis. Therefore, the interest rate should be considered in calculating the time value of the costs. In this study, the real discount rate considering the inflation rate was calculated for a more accurate analysis. Data such as inflation rate, electricity price growth rate and gas price growth rate were collected from the ECOS [23], Korea Electric Power Corporation (KEPCO) [37], and Korea City Gas Association (KCGA) [38].
- **Construction and repair cost:** For the economic assessment, the initial investment cost, the green remodeling construction cost, in this case, is required. In this study, green remodeling construction cost data were collected from user manuals for the Green Remodeling Analysis System that Korea LH provides [32]. In addition to the initial investment cost, information on repair cost or the maintenance cost incurred at regular intervals, was collected from the Korea Industrial Standard [39] and the Construction Association of Korea [40].
- **Benefit:** Not only the costs but also the benefits of energy consumption savings attributed to the application of green remodeling should be considered in the LCC analysis. To do this, information on the benefits that can be obtained when green remodeling is applied based on South Korea's policies was collected. These include electricity billing system [37], gas billing system [38], and Korean-certified emission reductions [41].

2.3. Step 3: Energy and environmental performance assessment

In this study, *EnergyPlus* v8.7 software, an open-source tool developed by the U.S. Department of Energy (DOE), was used to analyze the energy and environmental performance (i.e., energy consumption, and greenhouse gas (GHG) emission) of a building through the application of green remodeling. However, in *EnergyPlus* software, there is no graphic user interface that helps facilitate easy and convenient use of the tool. To make up for these shortcomings and to visualize the building, modeling was performed using *Design builder* v5 software.

2.3.1. Target building description

In addition, a case study was conducted on 'D' apartment located in Pohang, South Korea (latitude: 36.01°; longitude: 129.34°; elevation: 5 m). According to the Köppen climate classification, Pohang falls under the category of Cfa (humid subtropical climate) and is characterized by year-round precipitation and hot and humid summers. Table S1 gives a brief description of "D" apartment complex.

For the following reasons, this study performed the analysis on the household unit of the "D" apartment complex. First, green remodeling of the building unit cannot be performed solely based on the decision of the individual household. Second, it is difficult to calculate the cost sharing for the common area, because there are

various types of households in one apartment complex. Third, the green remodeling interest subsidy program applied to analyze economic performance in this study is supported by household units.

As described in section 2.1, households with a floor area of greater than 60 m² and less than 85 m² were selected for this study. In the 'D' apartment complex, there are two types of households (i.e., 75.7 m², and 84.97 m²) that meet the standard, but an energy simulation model was built for the 84.97 m² type (535 EA), which accounts for a large percentage. Fig. 1 shows the standard floor plan of the 84.97 m² type household in the 'D' apartment complex.

2.3.2. Estimation of the energy performance

GRCC considers three materials each in the building envelop part (i.e., wall, roof, and window) and equipment part (i.e., lighting, heating and cooling system, and boiler) when establishing scenarios for green remodeling. Four materials including wall, roof, window, and lighting present clear performance standards, but heating and cooling system, and boiler only present rough performance standards. Therefore, in this study, to assess the building's energy performance through green remodeling, energy simulation was performed by replacing three (i.e., wall, roof, and window) materials in the building envelop part and one (i.e., lighting) material in the equipment part into green remodeling materials [32]. The physical properties of the applied green remodeling materials are summarized in Table S2. The general material of building envelop part (i.e., wall, roof, and window) in Table S2 consists of the legal thermal transmittance data in 1999, which is the year of completion. The general material of the equipment (i.e., lighting) was set to be the lighting power density referring to ASHRAE standard 90.1 as lightings are replaced every 3 to 5 years. In this study, energy consumption of heating and cooling system, lighting, and

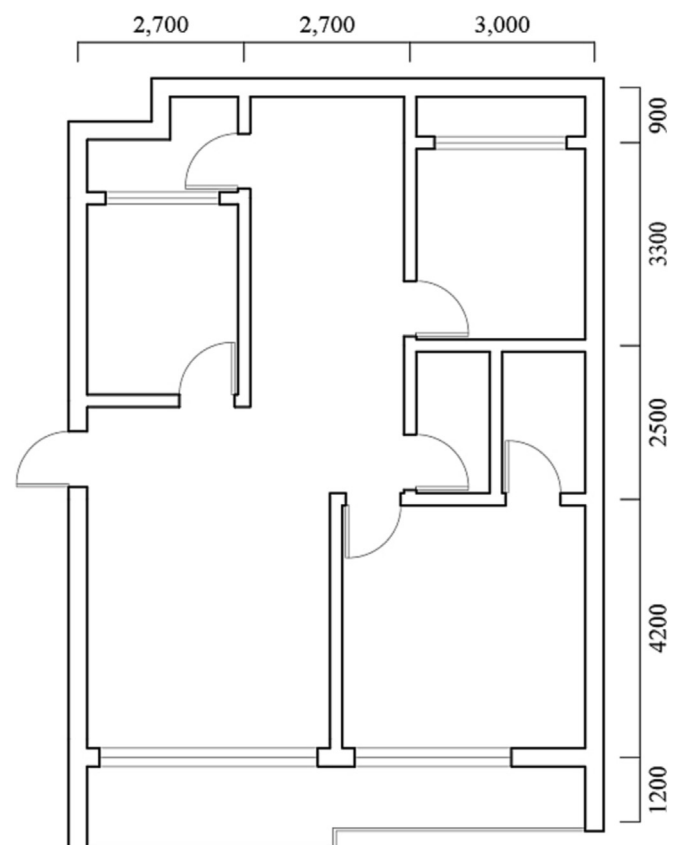


Fig. 1. Standard floor plan for 84.97 m² type household in 'D' apartment complex.

equipment were derived to analyze energy consumption savings attributed to the improvement of insulation and lighting performance.

In addition, the estimation performance of the energy simulation model was validated using the coefficient of variation of the root mean square error (CV(RMSE)) and mean bias error (MBE) provided by ASHRAE (refer to Eq.(1) and (2)). The ASHRAE guideline 14 specifies that the model is valid when CV(RMSE) is less than 15%, and MBE is less than $\pm 5\%$ in case monthly energy consumption data is used [42].

$$CV(RMSE) = \frac{\sqrt{\frac{\sum_{i=1}^n (AV_i - EV_i)^2}{n}}}{\frac{\sum_{i=1}^n AV_i}{n}} \times 100 \quad (1)$$

$$MBE = \frac{\sum_{i=1}^n AV_i - EV_i}{\sum_{i=1}^n AV_i} \times 100 \quad (2)$$

where, CV(RMSE) stands for coefficient of variation of the root mean square error, MBE stands for mean bias error, AV_i stands for actual value at i , EV_i stands for estimated value at i , and n stands for number of data.

2.3.3. Estimation of the environment performance

Environmental performance can be estimated via GHG emission reduction through energy consumption savings. Based on energy consumption savings (i.e., heating and cooling energy consumption, lighting energy consumption, equipment energy consumption) derived in 2.3.2, GHG emission reduction was calculated using GHG emission coefficients prescribed by the Enforcement Rules of the Energy Act. The GHG emission coefficients according to the type of energy are as follows (refer to Table S3) [43,44].

2.4. Step 4: Economic assessment of house remodeling

For the life cycle economic assessment of aging buildings that implemented green remodeling, main assumptions were established as follows: (i) analytical approach; (ii) starting point of analysis; (iii) analysis period; (iv) real discount rate; and (v) significant cost of ownership (refer to Table S4).

First, the present worth method was determined as an analytical approach in order to reflect the present value. Second, 'D' apartment complex, which is the target building, was completed in 1999. The 'Enforcement Regulations on the Corporate Tax Act' of the South Korea National Tax Service stipulate that the useful life of a reinforced concrete building is 40 years old [43]. Therefore, in this study, the starting point of analysis and analysis period were set at 2022 and 17 years, respectively. Third, in order to calculate the real discount rate, inflation rate was collected from ECOS [23], electricity price growth rate from KEPCO [37], gas price growth rate from KCGA [38], and KCERs growth rate from Korea Exchange [41], which were set at 0.87%, -0.83%, -4.34%, and 2.43%, respectively. Fourth, significant costs of ownership are divided into cost and benefit. The initial investment cost and repair cost are included in the cost. Table S5 shows the initial investment cost collected from GRCC [32]. Since Pohang where the target of the case study is located belongs to the southern region, the gray-shaded parts are applied for the economical assessment (refer to 2.2.2). Table S6 shows the construction cost database for lighting, also provided by GRCC.

The repair cost was collected from the Korean Standards Service Network [39], Korea Flat Glass Window Association [45], Construction Association of Korea [40], DesignBuilder Software [46], and U.S. DOE [47]. The benefit includes electricity bill savings, gas bill savings, and KCERs, which were collected from KEPCO [37], KCGA [38],

and Korea Exchange [41]. In South Korea, progressive electricity tariffs are applied to residential buildings including apartment complexes, and this was considered in this study.

Economic assessment results can be represented using the net present value (NPV). In general, when NPV is greater than 0, the project is considered economically feasible.

$$NPV_i = \sum_{t=0}^i \frac{B_t}{(1+r)^t} - \sum_{t=0}^i \frac{C_t}{(1+r)^t} \quad (3)$$

where, NPV_i stands for net present value at i , B_t stands for benefit at t , C_t stands for cost at t , r stands for real discount rate, i stands for period of life cycle.

2.5. Step 5: Setting goals to achieve 2030 CERT and 2050 carbon-neutrality

South Korea announced that it would reduce emissions by 32.8% in the building sector by 2030 and reach carbon-neutrality in 2050. Among major Asian countries like China, India, and Japan, that have higher carbon emissions than South Korea, also have plans to reduce carbon emissions. First, China aims to achieve carbon neutrality by 2060 after having a carbon emission peak before 2030. Second, India aims to reduce carbon emissions by 45% below 2005 levels by 2030 and achieve carbon neutrality by 2070. Third, Japan aims to reduce carbon emissions by 26% below 2013 levels by 2030 and achieve carbon neutrality by 2050. Compared to this, the 2030 CERT established by the South Korean government can be said to be more specific and intensive. In this regard, this study seeks to propose a green remodeling policy to achieve 2030 CERT and 2050 carbon-neutrality based on energy consumption savings through green remodeling and the current GRP in South Korea. To this end, annual energy consumption savings were estimated using the compound annual growth rate (CAGR) [48–50]. CAGR can be calculated using Eq. (4).

$$CAGR(y_0, y_n) = \left(\frac{EC(y_n)}{EC(y_0)} \right)^{\frac{1}{y_n - y_0}} - 1 \quad (4)$$

where, CAGR stands for compound annual growth rate, y_0 stands for first year, y_n stands for final year, $EC(x)$ stands for energy consumption in year x .

However, in the annual energy consumption savings estimated using CAGR, energy consumption savings through green remodeling were not taken into account. This study attempts to consider the energy consumption savings attributed to the application of green remodeling with the use of variant CAGR (vCAGR), which can be calculated using Eq. (5).

$$vCAGR(y_0, y_n) = \left(\frac{EC(y_n) \times (1 - ECSR)}{EC(y_0)} \right)^{\frac{1}{y_n - y_0}} - 1 \quad (5)$$

where, vCAGR stands for variant compound annual growth rate, y_0 stands for first year, y_n stands for final year, $EC(x)$ stands for energy consumption in year x , ECSR stands for energy consumption saving rate.

To determine whether the building sector's 2030 CERT and 2050 carbon-neutrality can be achieved through CAGR and vCAGR, energy consumption data are needed from a long-term perspective. Therefore, in this study, the final energy consumption of the private building sector in 2000 and 2018 was collected by referring to the 2019 Energy Statistics Yearbook published by the Korea Energy Economic Institute, and was recorded at 32,639,000 toe and 40,088,000 toe, respectively [51].

3. Results and discussion

3.1. Energy and environmental performance analysis result through green remodeling

In this study, energy consumption values obtained before and after green remodeling for the 84.97 m² type household of 'D' apartment complex, were compared to analyze the energy consumption saving effects attributed to the application of green remodeling (refer to Table S7). Energy consumptions before and after applying green remodeling were drawn based on real data obtained from REB, and energy simulation conducted through *EnergyPlus* v8.7 software, respectively. Electricity and gas consumption data were collected from 1,220 households in the 'D' apartment complex. Outliers that have the potential of leading distorted or biased results in energy consumption comparison and are analyzed to be unreliable among real datasets are considered as missing data. The outliers are defined as households with (i) zero energy consumption, or (ii) energy consumption outside the 1.5 × interquartile range (IQR) of the dataset. Lastly, the average energy consumption was derived based on the data of 321 households in gas consumption and 490 households in electricity consumption among the 84.97 m² type households. However, the energy consumption data collected in this study is specifically regarding the target, 'D' apartment complex. So it may differ from the general energy consumption pattern. As described in Section 2.3.2, ASHRAE specifies that the validity of the simulation model is verified when the CV(RMSE) of the energy consumption model is less than 15%, and MBE is less than ± 5%. The energy simulation model in this study was validated with CV(RMSE) and MBE within the standard range as shown in Table S8.

Fig. 2 is a graph showing the monthly electricity consumption presented in Table S7. Electricity consumption mainly consists of cooling system such as air conditioning, equipment and lighting. Before applying green remodeling, the yearly electricity consumption of 84.97 m² type household was 3,128.41 kWh. By replacing the envelope and the lighting of the building with green remodeling materials, the annual electricity consumption was reduced to 2,934.64 kWh. South Korea has four distinct seasons, and in general, energy for cooling is consumed the most in summer, specifically from June to August. Thus, the highest electricity consumption was recorded in July, the midsummer, for both before and after the green remodeling implementation. Thermal retrofitting by enhancing thermal transmittance is determined to be effective as the electricity consumption was reduced in cooling season.

Also, a comparatively large decrease was shown in winter, from December to February. [52]. According to the Economics Institute, electricity consumption during winter has increased rapidly since the mid-2000 s. This is due to the increase in public demand for heating appliances using electricity since electricity rate hikes have been controlled by government regulations. Gas prices, however, have risen significantly due to a sharp rise in international oil prices [53]. In this study, the heating and cooling set points were set at 21 °C and 29 °C, respectively, based on the previous research conducted by Jeong et al. [52]. The Meteorological Data Open Portal of the South Korea Meteorological Agency shows that the temperature ranges from 20.6 to 29.1 °C in the summer and from −4.1 to 6 °C in the winter, respectively, for the past 10 years [54]. The difference between the indoor and outdoor air temperatures is much larger in the winter than in the summer, which suggests that the effect of thermal transmittance is greater in the winter. As Fig. 2 demonstrates, monthly electricity consumption recorded the biggest difference in the summer (i.e., July: 23.06kWh) and winter (i.e., Jan.: 46.77kWh). Electricity consumption saving occurs after the application of green remodeling (i.e., 3,128.41kWh to 2,934.64kWh).

Fig. 3 is a graph showing gas consumption before and after the green remodeling. In buildings, gas is mainly used for heating and hot water supply, so gas consumption shows high values in winter. During the heating season, specifically from December to February, there are clear differences between the energy consumption before and after the green remodeling (i.e., Feb.: 1,010.51 MJ). However, as the outdoor temperature gradually rises, this difference gradually decreases. Although gas consumption savings through green remodeling are insignificant in seasons other than winter, consequently yielding gas consumption saving (i.e., 26,489.18 MJ to 22,363.20 MJ).

Consequently, both electricity and gas consumption were reduced after green remodeling was implemented. Specifically, electricity consumption was reduced by 6.19% and gas consumption also decreased by 15.58%. It can be confirmed that thermal retrofits through green remodeling, such as enhancing the thermal transmittance of building envelopes and replacing lighting equipment, are effective in reducing energy consumption.

Based on the energy consumption reduction, environmental performance can also be estimated by applying the GHG emission coefficient in Table S3. The 84.97 m² type household of 'D' apartment complex can reduce electricity consumption of 193.77kWh and gas consumption of 4,125.98 MJ per year, thereby reducing annual GHG emissions of 0.34tCO_{2eq}.

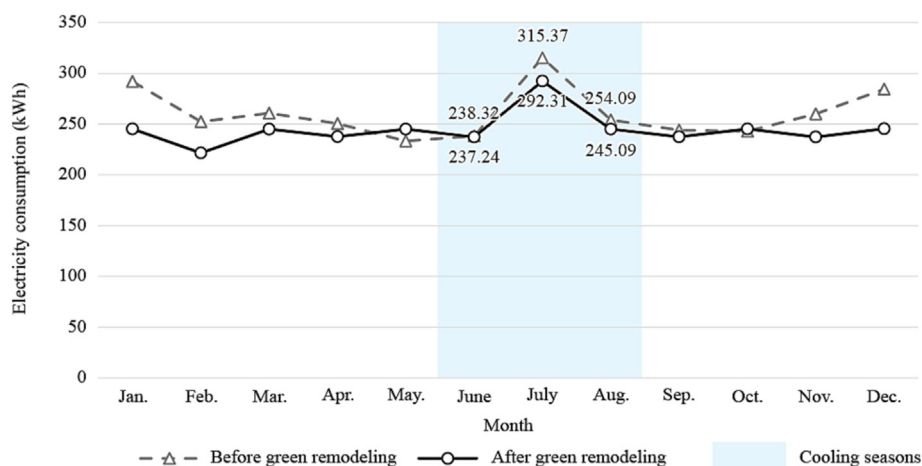


Fig. 2. Electricity consumption according to green remodeling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

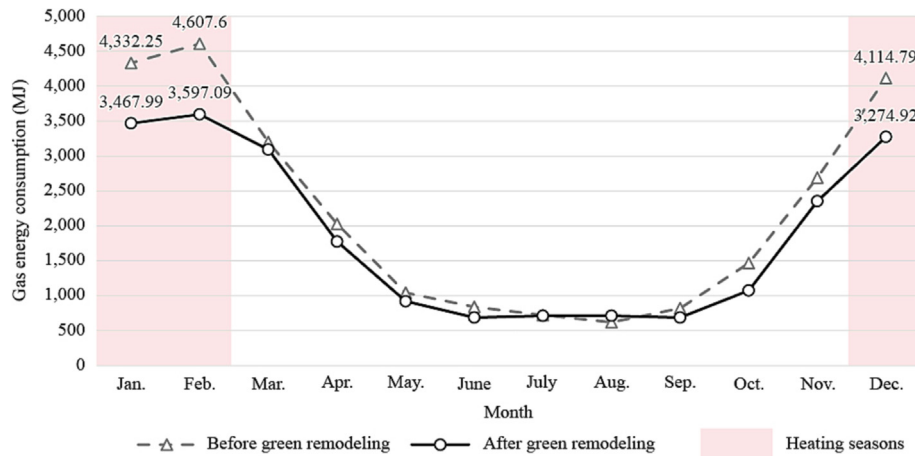


Fig. 3. Gas consumption according to green remodeling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Economic analysis results according to financing scenarios

In this study, four financing scenarios were established on the basis of the three loan programs collected in Section 2.2.1. Economic assessment was performed based on these scenarios (refer to Fig. 4).

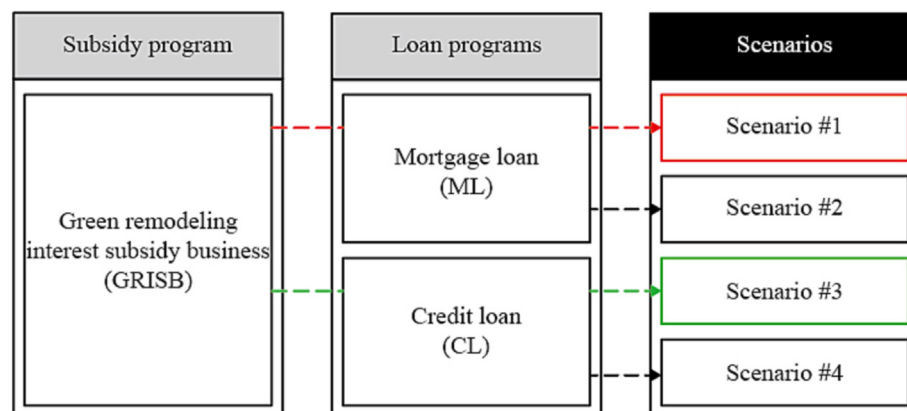
First, in terms of NPV_{17} , scenario #3 has the highest economic feasibility (i.e., USD-46,054.85), whereas scenario 2 has the lowest economic feasibility (i.e., USD-50,716.66). However, in all scenarios, NPV_{17} is less than 0, making it impossible to ensure economic feasibility (refer to Table S9). This is because the cost required for green remodeling greatly outweighs the benefit. For example, when green remodeling is applied to a 84.97 m² type household, a benefit of USD 1,650.48 can be obtained from energy consumption reduction, and a benefit of USD 74.18 from the sale of KCERs for 17 years. On the other hand, the financial cost and repair cost required to apply green remodeling range from a minimum of USD -47,779.51 to a maximum of USD -52,441.32. This suggests that additional support or benefits other than GRISB are needed to ensure the economic feasibility of green remodeling implementation.

Second, the economic feasibility of each scenario was found to vary according to the point in time of analysis after green remodeling implementation (refer to Table S10 and Fig. 5). For example, scenario #2 had the highest NPV_1 (i.e., USD-2,975.51) but the low-

est NPV_{17} (i.e., USD-50,716.66), whereas scenario #3 had the lowest NPV_1 (i.e., USD-5,898.96) but the highest NPV_{17} (i.e., USD-46,054.85). This is because the subsidy program and loan program applied to each scenario are different. In scenarios #1 and #3, GRISB was applied along with mortgage loan and credit loan, respectively (refer to Fig. 4). Consequently, NPV decreased sharply for 5 years after the application of green remodeling (i.e., scenario 1: USD-4,706.73 to USD-23,101.70; and scenario 3: USD-5,898.96 to USD-28,960.88), but the amount of NPV decrease was reduced afterwards. On the other hand, only mortgage loan and credit loan were applied to scenarios #2 and #4, respectively. Therefore, although the initial amount to be repaid is relatively low, NPV_{17} is low due to high interest rates applied over a long period. This result suggests that a proper loan strategy needs to be devised according to the cash flow of each household.

3.3. Policy proposals regarding green remodeling to achieve the 2030 CERT and 2050 carbon-neutrality

In this study, a trend analysis on energy consumption was performed by calculating the CAGR based on the yearly energy consumption data in the private building sector, including residential and commercial buildings, from 2000 to 2018 (refer to Eq.(4)). The CAGR of the private building sector was 1.41%, which was then applied to the energy consumption in 2018



Note: scenario #1=GRISB+ML, scenario #2=ML, scenario #3=GRISB+CL, scenario #4=CL

Fig. 4. Scenario establishment according to subsidy program and loan programs.

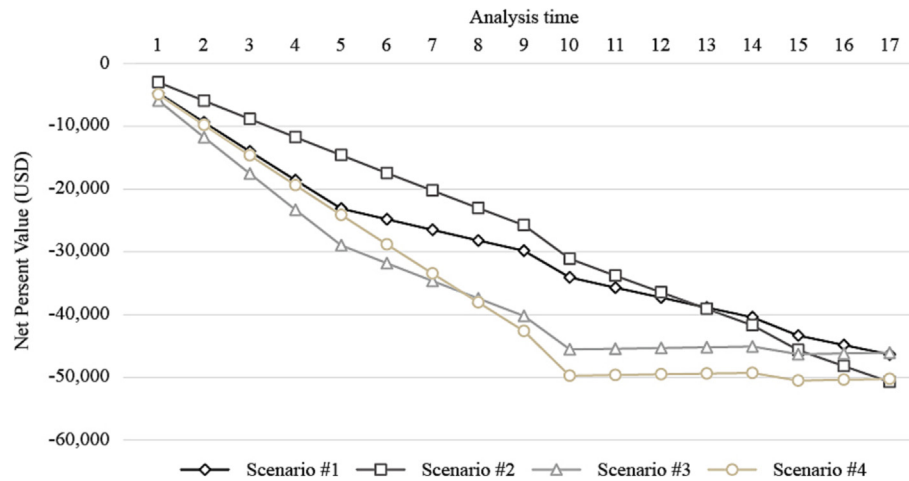


Fig. 5. Net Present Value according to Analysis time.

announced by the Korea Energy Agency to derive the energy consumption below BAU in the building sector in 2030 and 2050. This was estimated to be about 568,550,038 MWh and 741,335,441 MWh, respectively (refer to Table S11).

The South Korean government aimed to reduce this value by 32.8% (191,102,958 MWh) in 2030 and by 100% in 2050. To this end, an analysis was performed by combining the interest rate of credit loan and the interest support rate of GRISB based on scenario #3 with the best economic feasibility in section 3.2. Fluctuations in credit loan interest rates were collected from ECOS [23]. ECOS provides interest rates for 21 years from 2001 to 2021, and it was confirmed that the credit loan interest rate in 2008 was the highest at 8.44% due to the global financial crisis resulting from subprime mortgage loans. In this study, the interest rate of credit loan and the interest support rate of GRISB were discrete from 1% to 8.44% at 1% intervals (i.e., 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, and 8.44%).

3.3.1. Utility analysis of GRISB according to interest rate and interest support rate

As mentioned in Section 2.2.1, households wishing to apply green remodeling can receive support for an interest rate of 3% from GRCC for loans of up to USD14,015.42. Based on the current status, the amount of support that households with an initial investment cost of USD14,015.42 or more can receive is USD1,119.84. However, interest rates change several times a year. Therefore, in this study, subsidy amounts per household were calculated according to the loan interest rate and interest support rate of GRISB (refer to Table S12).

The amount of support that households can receive increased as the credit loan interest rate and the GRISB interest support rate increased (i.e., USD359.14 to USD3,213.14). However, in order to achieve 2030 CERT and 2050 carbon-neutrality, the South Korean government needs to support as many households as possible with a limited budget. The total budget of GRISB for 2022 is USD7,007,708. Table S13 shows the number of households that can receive support according to the interest rate and interest support rate derived from the above.

The number of households eligible for government support for annual interest according to the credit loan interest rate and the GRISB interest support rate was a maximum of 19,512 to a minimum of 2,181 (refer to Table S13). As analyzed earlier, the 84.97 m² type household can reduce GHG emissions of 0.34tCO_{2eq} annually with green remodeling. However, with the current budget, a reduction in GHG emissions is estimated to be 6,570tCO_{2eq} per year and 45,990tCO_{2eq} by 2030, which is 0.5% of the 2030 CERT,

87,907,361tCO_{2eq}. Therefore, the South Korean government should devise other measures besides the current GRISB to achieve 2030 CERT and 2050 carbon-neutrality.

3.3.2. Proposal of financial policy to induce participation in green remodeling

The South Korean government can increase the rate of participation in green remodeling in two ways: (i) encourage participation in green remodeling through subsidy payments; and (ii) encourage participation in green remodeling by imposing penalties.

Prior to the analysis, three assumptions were made: (i) standard construction cost per m²; (ii) remodeling cost per m²; (iii) apartment complex remodeling type. First, according to the 'construction costs for basic type and additional costs of housing subject to the sale price ceiling system' announced by MOLIT in 2022, the ground floor construction cost for 11 to 15 story-apartment is set at USD1,339.17/m² [55]. Second, a general cost level for remodeling is required because building remodeling costs vary according to the scope and level. Therefore, in this study, the remodeling cost was limited to 20% to 30% of the construction cost based on the 'remodeling project cost by stages' of the Committee on Library and Information Policy, which is the only remodeling project cost standard presented by public institutions [56]. Third, according to 'A Proposal on Remodeling Techniques for Customized Remodeling Support' published by MOLIT in 2013, a remodeling project is carried out at the level of performance maintenance for apartment complexes [57]. Therefore, in this study, it was assumed that the general remodeling cost of an 84.97 m² type household is USD22,757.91 - USD34,136.86 (USD1,339.17x84.97x0.2 ~ 0.3), and the energy performance is the same. Table S14 shows the NPV₁₇ analysis results according to the interest rate of credit loan based on the remodeling costs.

First, a subsidy payment can encourage participation in green remodeling. In general, NPV ≥ 0 means that the project is economically feasible. Table S14 shows NPV₁₇ analysis results on the 84.97 m² type household.

The NPV₁₇ of the 84.97 m² type household decreased as the interest rate of credit loan increased and the interest support rate of GRISB decreased. This is because the cost increases as the amount of repayment increases with increasing interest rate, but the benefits from energy bill savings and profits from the sale of KCERs are the same (refer to Table S9). On the other hand, the NPV₁₇ of a typical 84.97 m² type household ranged from USD-23,924.24 to USD-50,658.43, which was lower compared to that

of the green remodeling case by up to USD17,713 according to the interest rate (refer to Table S15). Accordingly, the South Korean government should provide subsidies of up to USD17,713 per household so that households wishing to perform general remodeling can select green remodeling.

Second, imposition of penalties can be considered to encourage participation in green remodeling. As of 2021, 28 countries around the world, including the United Kingdom, Finland, Norway, have introduced and operated carbon taxation [58], where a tax is imposed on carbon emissions. It is expected that if the penalty through carbon taxation is lower than NPV₁₇ of green remodeling, the household will voluntarily participate in green remodeling. The energy and environmental performance analysis results in 3.1 show that the 84.97 m² type household emits 3.03tCO_{2eq} of GHG annually, and the annual GHG emission can be reduced to 2.69tCO_{2eq} through green remodeling. As analyzed earlier, an additional cost of up to USD17,713 is required for green remodeling compared to general remodeling. In other words, if an annual carbon taxation of up to USD3,064.53/tCO_{2eq} is imposed as of 2022, the cost incurred from carbon taxation for 17 years will be higher than the cost attributed to the application of green remodeling, which in turn encourages participation in green remodeling. However, since the subsidy payment or penalty imposition is not sustainable because it will cost too much, a great deal of resistance is expected due to policy implementation.

3.4. Discussion

Even if the private building sector achieves 100% green remodeling participation rate, the GHG emission reduction is 12.78% by 2030 and 30.55% by 2050, which falls short of the target (refer to Table S16, and Eq. (5)). In other words, it is difficult to achieve 2030 CERT and 2050 carbon-neutrality with green remodeling through GRISB alone.

In order for South Korea to achieve 2030 CERT and 2050 carbon-neutrality, the following policies can be proposed. First, financial policies such as the current GRISB need to be revised. GRISB is focused only on funding, which limits the scope of support. To address this problem, it is necessary to expand the total budget of green remodeling interest support business and adjust interest support rate according to the interest rate of each year [59,60]. It is also possible to review and introduce various financial policies, such as tax exemption or deduction and carbon taxation in addition to providing loan interest support [61]. Second, as shown in section 3.2, improving only the building envelope materials is not enough to ensure sufficient economic performance. This means that other profit structures are necessary besides energy consumption savings by improving the building envelope materials. One of the most possible methods to reduce energy consumption besides passive systems, the introduction of active systems (i.e., solar PV system, micro wind turbine) and the sale of surplus resources (i.e., electricity) can be considered to improve profit structures with the application of green remodeling. According to previous studies, profit of up to USD828.3 per year can be obtained if solar PV systems and P2P electricity trading are introduced in South Korea [62]. Third, according to Table S16, even if the green remodeling participation rate of 100% is achieved in the private building sector, only 12.78% of the 2030 CERT and 30.55% of the 2050 carbon-neutrality can be achieved. In this situation, in 2022, only 7,217 cases of green remodeling were carried out, which is less than half of the government target (i.e., 20,000 cases per year). However, according to the analysis in section 3.3, inducing participation through subsidy or penalty is not realistically sustainable. In other words, in addition to economic factors, a plan to induce green remodeling participation must be devised. Lee et al. (2016) derived the factors inhibiting green remodeling through a survey

of experts, and consequently, excluding economic factors and lack of awareness of green remodeling were found to be the biggest barriers [63]. Similarly, a lot of previous studies found that the introduction of knowledge and information policies, can promote green remodeling based on the case of households applied with successful green remodeling project [64–66]. Many previous researches pointed out that it is important to have easy access to information related to building retrofit or remodeling, including process, subsidy, loans, reliable experts, options, etc [67–69]. The South Korean government also promotes green remodeling as part of South Korea's GND, but many households are not aware of the related policies, which can have a negative impact on financial decision-making. Finally, South Korea cannot achieve 2030 CERT and 2050 carbon-neutrality through policies such as payment of incentives or imposition of penalties. Therefore, it needs to improve energy efficiency through R&D in building energy saving technology and nurture experts at green remodeling.

4. Conclusions

This study sought to analyze the feasibility of existing green remodeling policies in South Korea, and subsequently propose policies for enhanced utility so that the GRP designed to reduce GHG emission gaps cannot be scaled down due to current risks such as interest rate hikes. To achieve the research aim, a database was established for energy simulation and economic assessment. To assess the effects of energy consumption savings of green remodeling, energy simulation was performed using *EnergyPlus* v8.7 and *Designbuilder* v5 software, and the economic performance for each scenario attributed to the application of GRISB was evaluated using LCC analysis. The effectiveness of the current GRP was analyzed, and policy directions were proposed. A case study was also conducted on the 84.97 m² type household of 'D' apartment complex located in Pohang, South Korea. The main findings of the research are as follows:

- Applying green remodeling to an 84.97 m² type household reduced yearly electricity and gas consumption saving by 6.19% and 15.58% respectively, indicating energy saving effectiveness of green remodeling.
- Economic assessment results showed that in terms of NPV₁₇, scenario #3 has the highest economic feasibility (i.e., USD-46,054.85), whereas scenario #2 has the lowest (i.e., USD-50,716.66). NPV₁₇ was less than zero in all scenarios, which indicates that it is not possible to ensure economic feasibility.
- The analysis found that the economic feasibility of each scenario differed depending on the point in time the analysis was done. This suggests that there is a need to devise an appropriate loan strategy according to the cash flow of the household.
- Analysis of the current GRISB policy confirmed that GHG emission, which is only 0.5% of 2030 CERT, can be reduced with the current budget. In addition, it was found that a subsidy of up to USD17,713 is provided, or a carbon taxation of up to USD3,064.53/tCO_{2eq} per year can be imposed to ensure economic feasibility, but this policy is not sustainable.

Based on these results, this study proposes the following GRPs to achieve 2030 CERT and 2050 carbon-neutrality: (i) revise financial policies such as securing the total budget and adjusting interest support rates, (ii) improve profit structures by enabling the sale of surplus resources arising from the introduction of active systems, (iii) increase public awareness of green remodeling and encourage participation through knowledge and information policy, and (iv) improve energy efficiency via research and development of building energy saving technologies.

This study is expected to help revise South Korea's GRP through the following contributions: (i) analyze the budget required to promote green remodeling and help establish a sustainable GRP; (ii) estimate the reduction of GHG emissions to achieve 2030 CERT and 2050 carbon-neutrality and set the target performance values of green remodeling materials based on the GHG emission reduction to improve the energy performance of aging buildings; (iii) when an active system is introduced, energy consumption in sectors other than the building sector can be reduced from the sale of surplus resources, which can serve as a basis for the introduction of P2P energy trading. Despite these contributions, this study poses the following limitations. First, the research was conducted only on the 84.97 m² type household, as it is the most common residential type in South Korea. In addition, energy performance and economic performance may vary depending on the region and household size. Second, there are significant differences in costs according to the level and scope of remodeling, which makes it difficult to present clear standards for project costs. Third, in this study, the heating and cooling setpoints were set based on the literature to estimate heating and cooling energy consumption, but to obtain more accurate results, a real occupant schedule and heating and cooling setpoints should be applied to a single household.

Based on these limitations, directions for future studies are suggested as follows. First, features such as types of households, regions, household sizes and remodeling scenarios should be diversified for generalized analysis. Also, this study has proposed general directions of policies based on existing policies from various countries. Future studies should analyze the feasibility of the proposed policies in global aspect and propose specific policies regarding implementation. Lastly, expanding the scope of analysis to the aspects of countries and sectors is required as this study mainly analyzed targeting the building sector of South Korea.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2023.113059>.

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